Advanced Pair Telescope Concept

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Future Space-Based Gamma-Ray Observatory Workshop

GSFC

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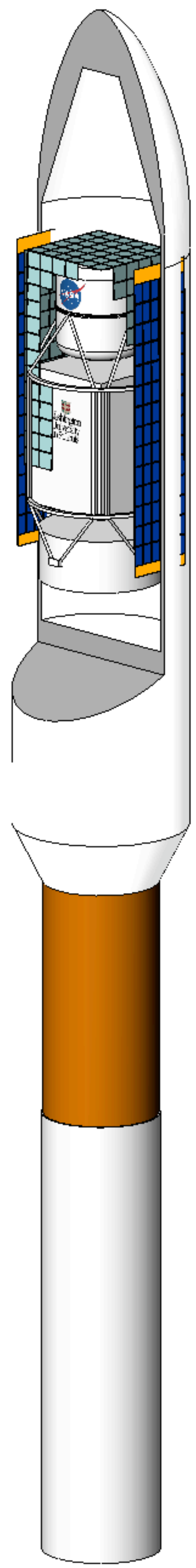
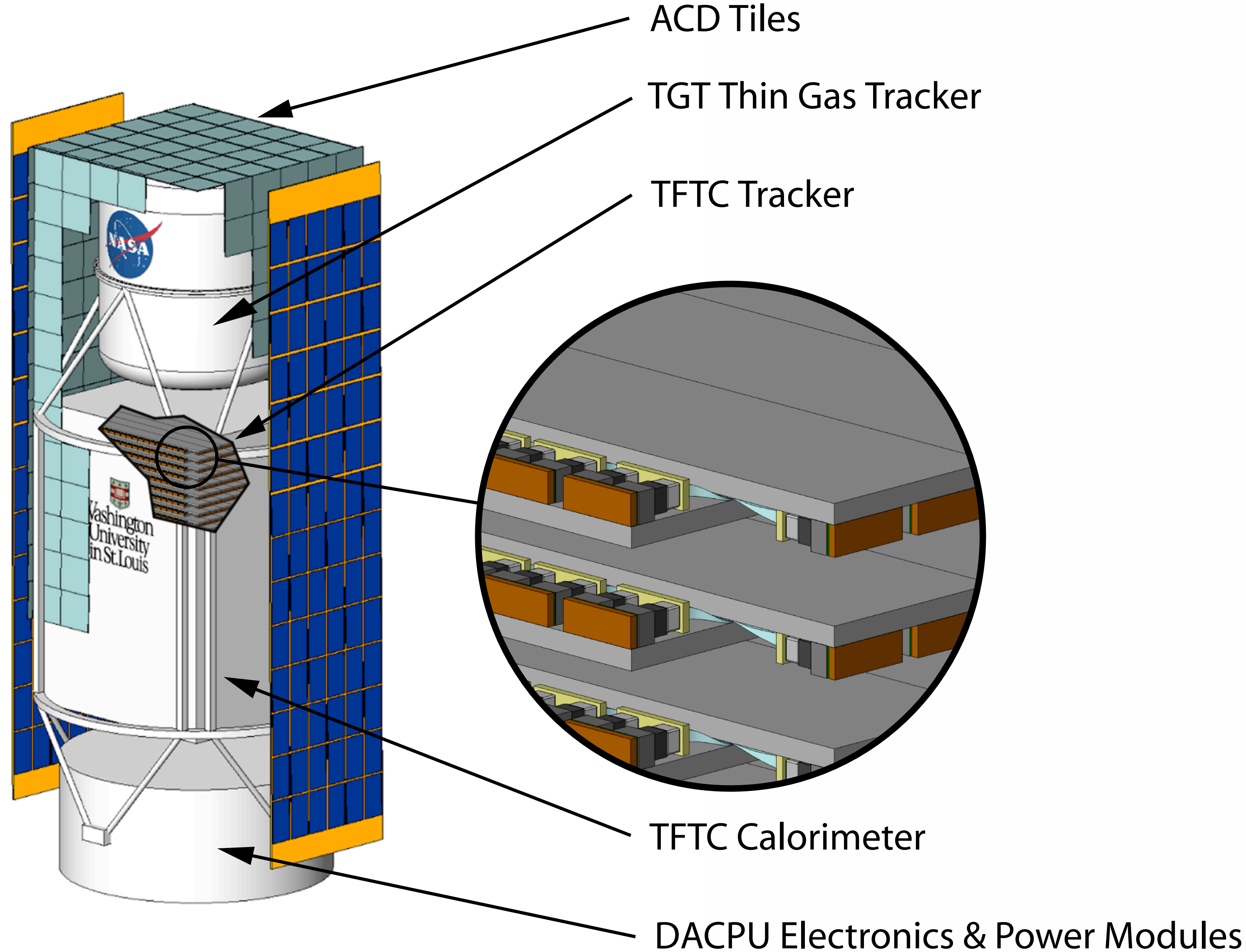
APT Concept

APT Proposal (2007): *submitted to Astrophysics Strategic Mission Concepts RFP*, J. Buckley, W. R. Binns, G. DeNolfo, A. Drlica-Wagner, N. Gehrels, S. Hunter, H. Krawczynski, J. Link, J. McEnery, G. Varner



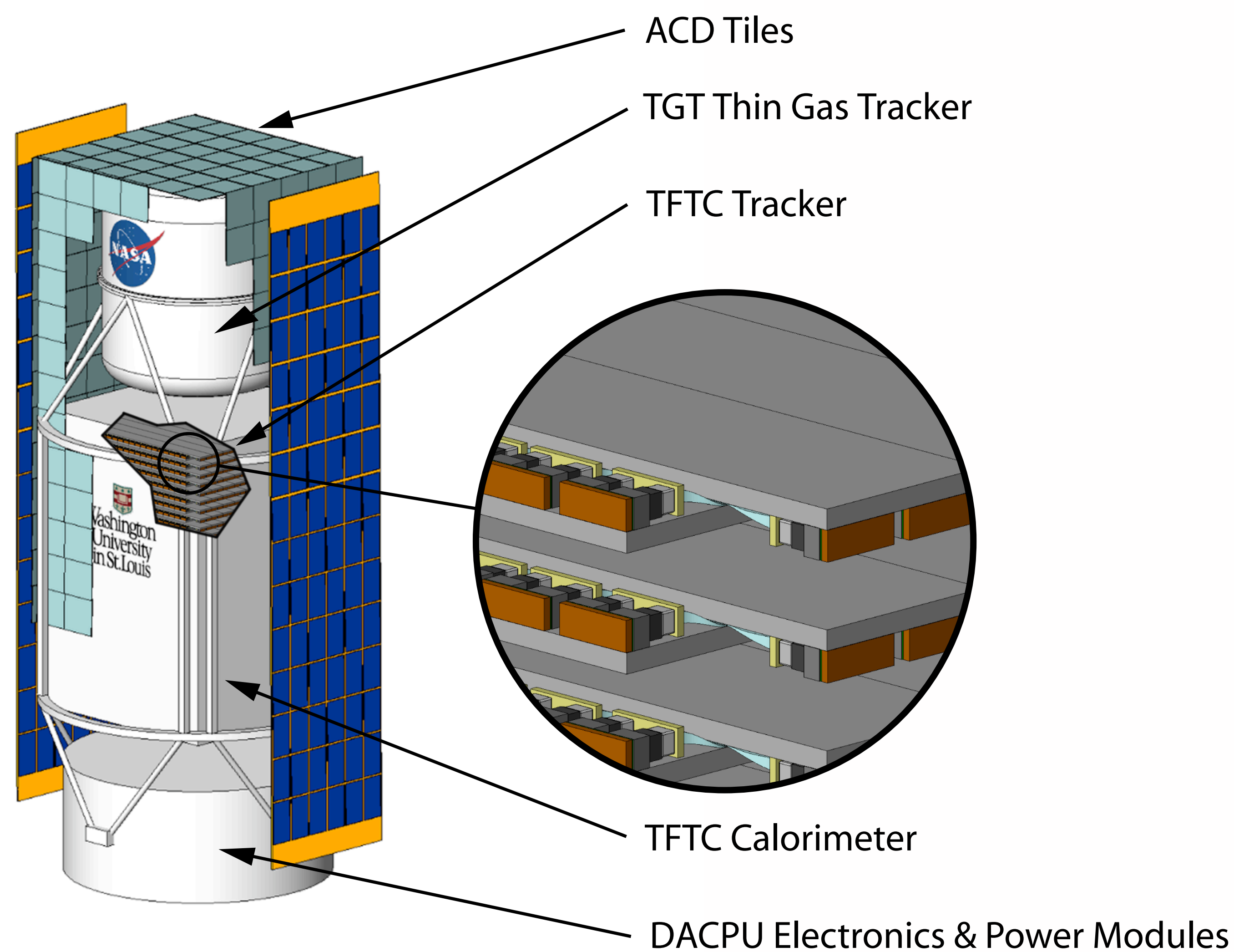


APT Concept

- **Instrument Concept**

  ✳ Much Fermi science came from >GeV energies (where resolution is good, diffuse backgrounds are manageable) and < 100 GeV (where statistics are good) - *Next generation instrument should be optimized on the sweet spot around a few GeV.*

  ✳ Increase geometry factor by >10 times Fermi - scintillating fibers.



  ✳ Improve angular resolution by >3 in range 100 MeV - 10 GeV.

  ✳ Trade calorimetry (weight) for geometry factor (leave 100 GeV to ground-based instruments) - hold energy resolution to <30% up to 10 GeV, <50% up to 30 GeV.

  ✳ Explore use of deployable technology to achieve larger volume better angular resolution, without simple volumetric cost for a probe-scale (~600M$) mission including a gas TPC for MeV measurements.

APT Concept

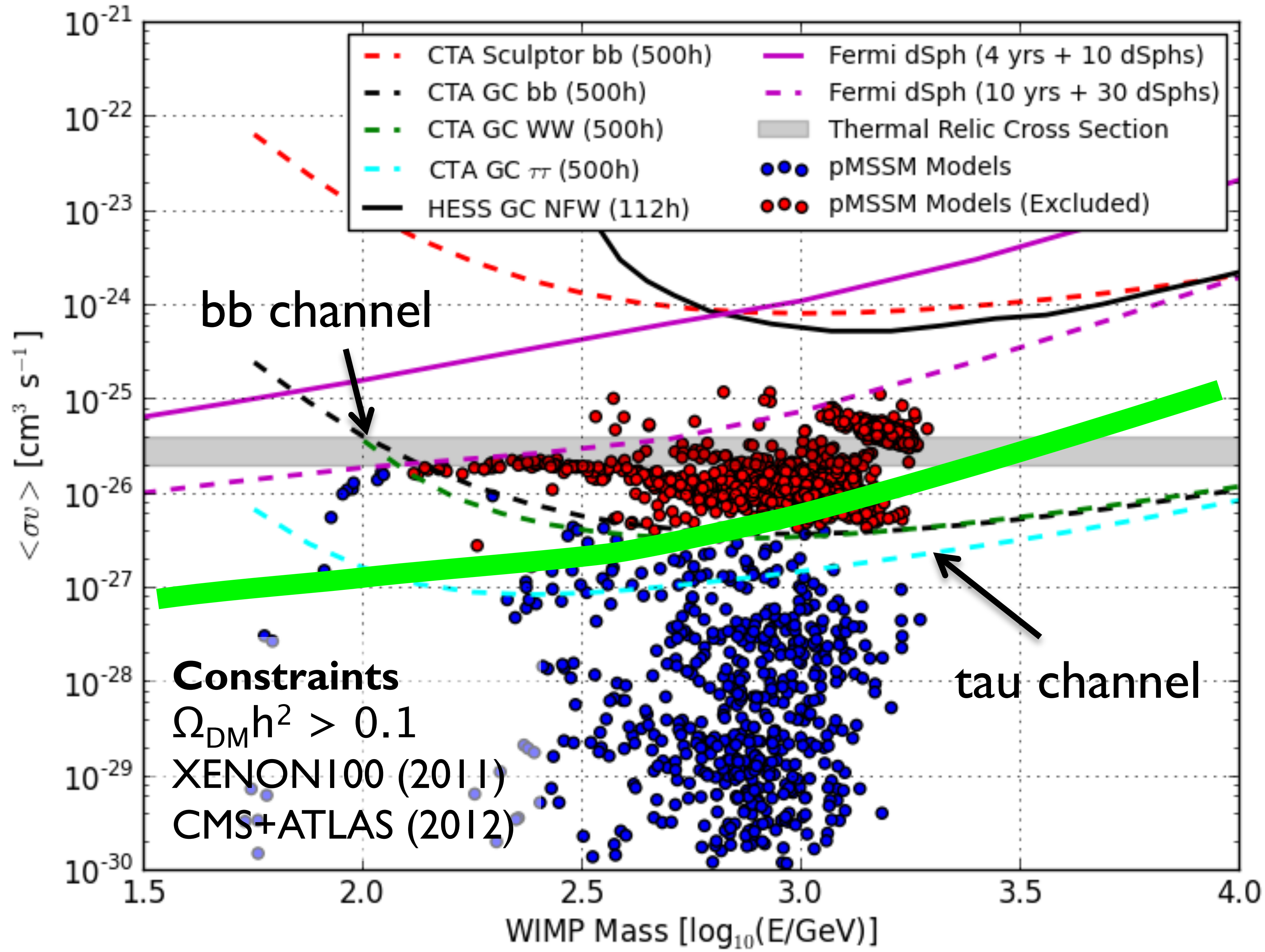
- **Science** (Enabled by 10x LAT geometry factor, >3 times angular resolution, optimized performance at a few GeV) Probe most of natural **Dark Matter** parameter space using dwarf galaxies.

  - ✳ Make **spatially resolved images of galactic sources** such as the GC region, SNR and PWN to understand details of particle acceleration.

  - ✳ Make **all-sky temporally dense measurements of transient phenomena** for large-Z GRB/PopIII SNae, EM counterparts of gravity wave sources, perhaps Hubble constant constraints from AGN autocorrelations and gravitational wave detections.

  - ✳ Make measurements of **pair halos** around AGNs, providing first solid constraints on primordial magnetic fields, with chirality probe CP violation in early universe, **baryogenesis / matter-antimatter asymmetry in the universe** (perhaps with MeV search for redshifted GeV annihilation signal - P. Coppi)

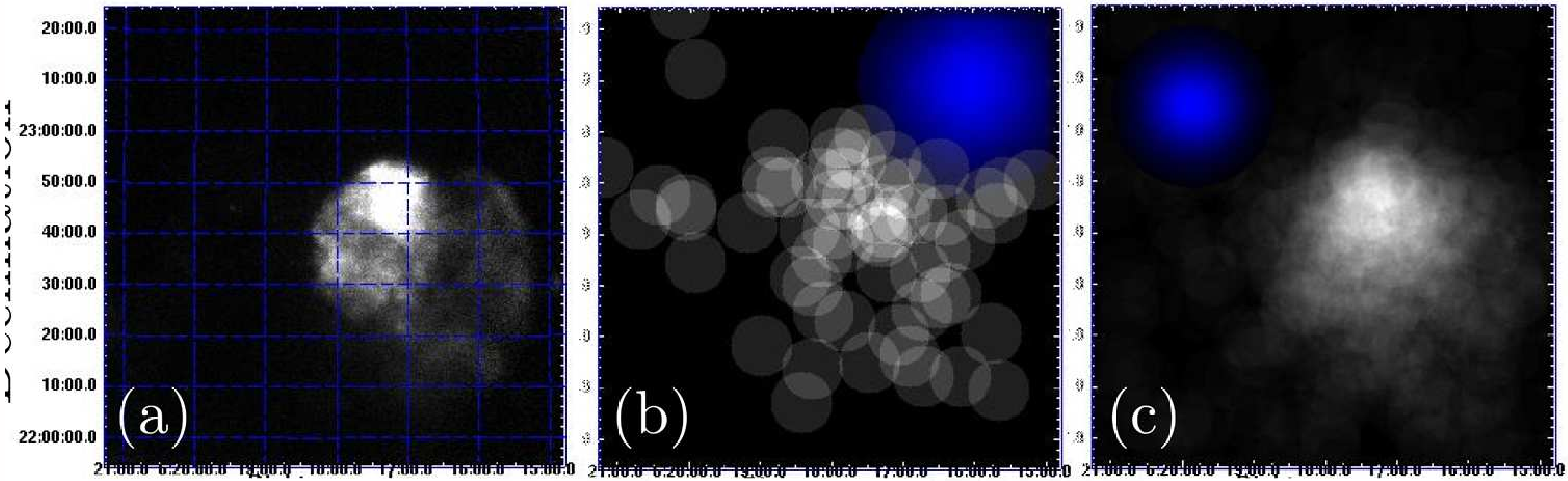
Science - Dark Matter



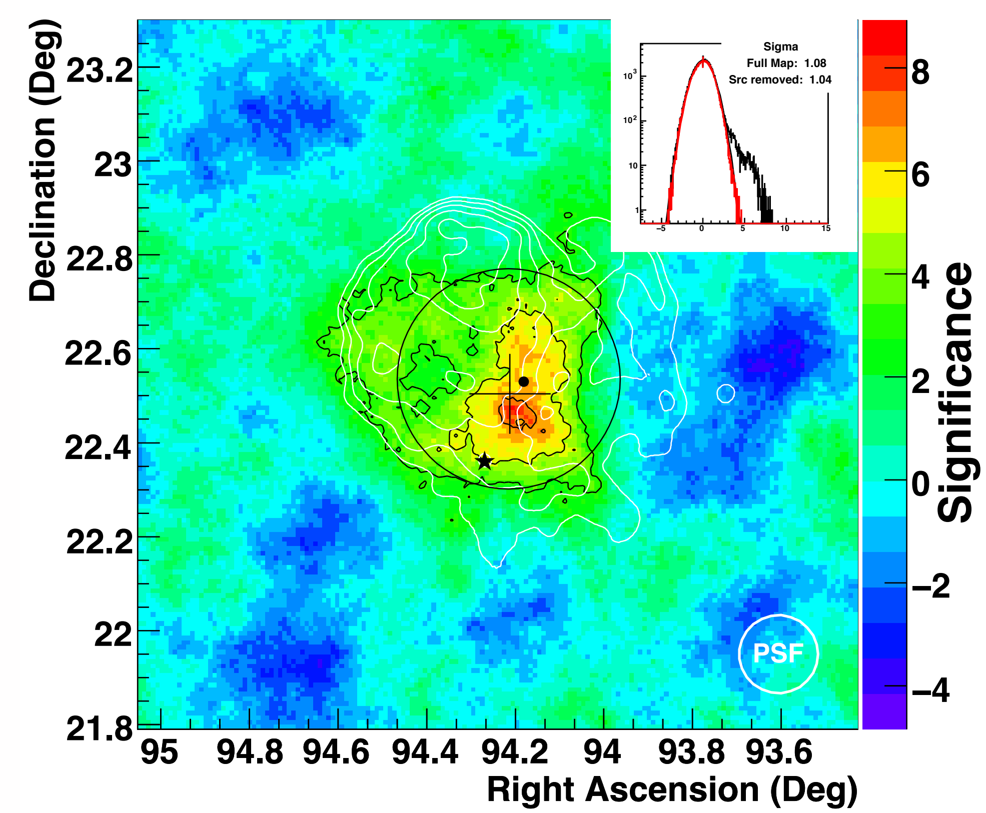
Photon-count-limited regime - sensitivity AND cross section limits should scale roughly proportional to the geometry factor, number of Dwarf galaxies

Angular Resolution - SNR Case Study

IC443 - PSPC | IC443 - >10 GeV LAT Sim. | APT Sim

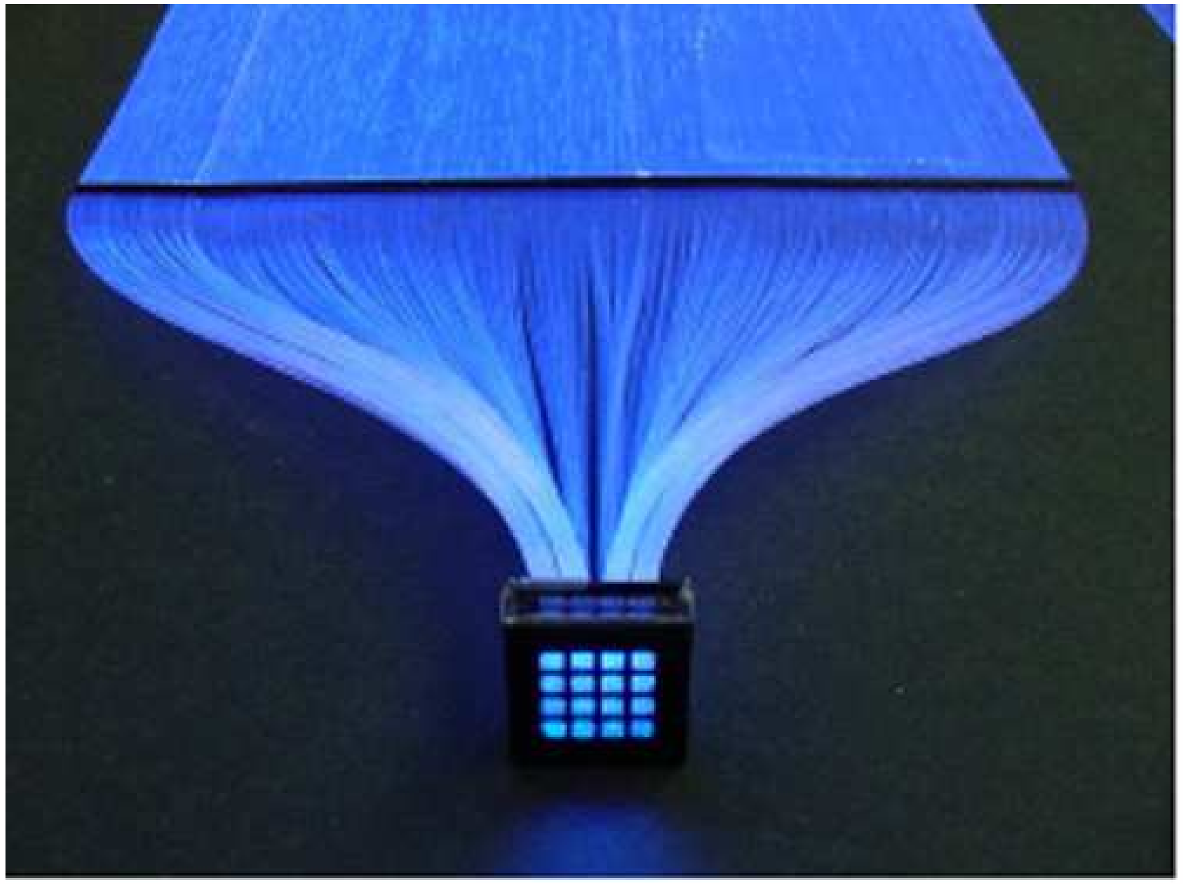


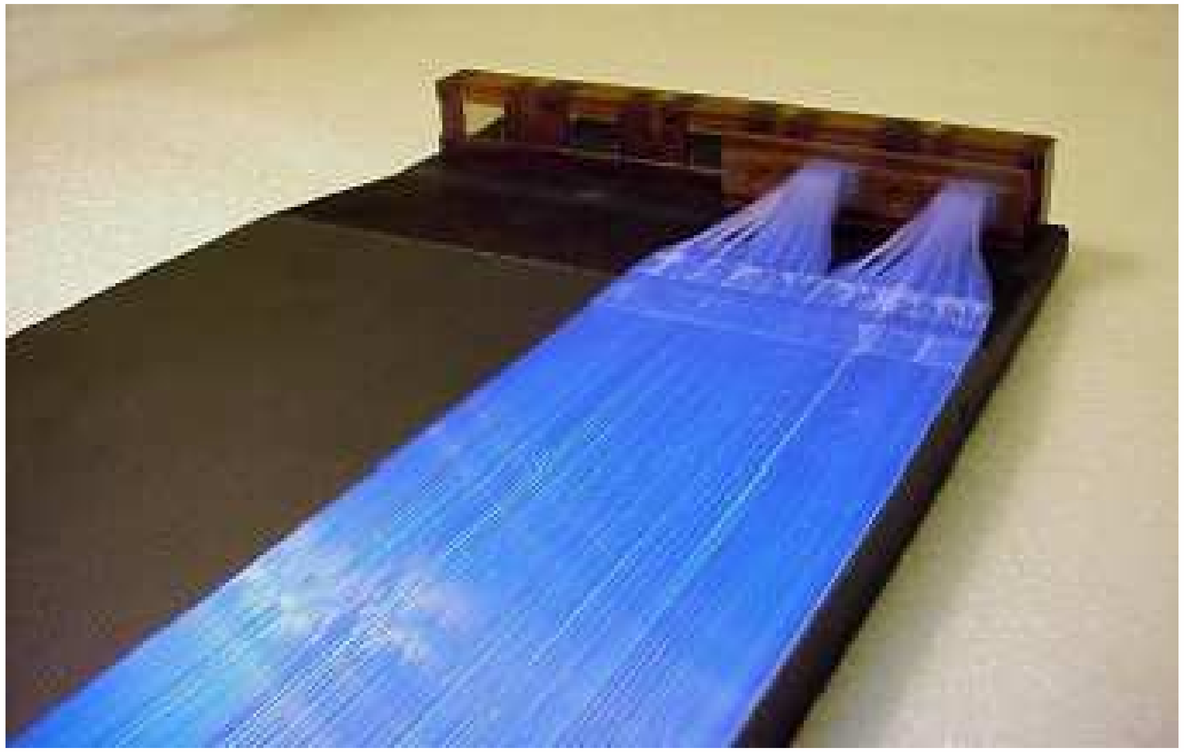
IC443 - VERITAS Discovery Paper



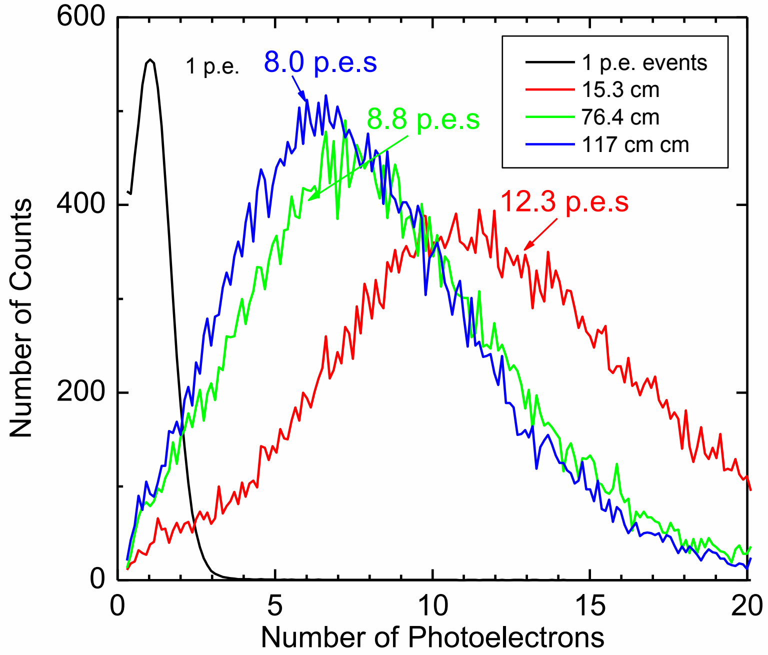
- APT would allow detailed probes of the SNR morphology, resolving regions with molecular clouds, magnetic field amplification.
- Use ground-based measurements to provide lever arm for spectral morphology.

Fiber/MAPMT Performance

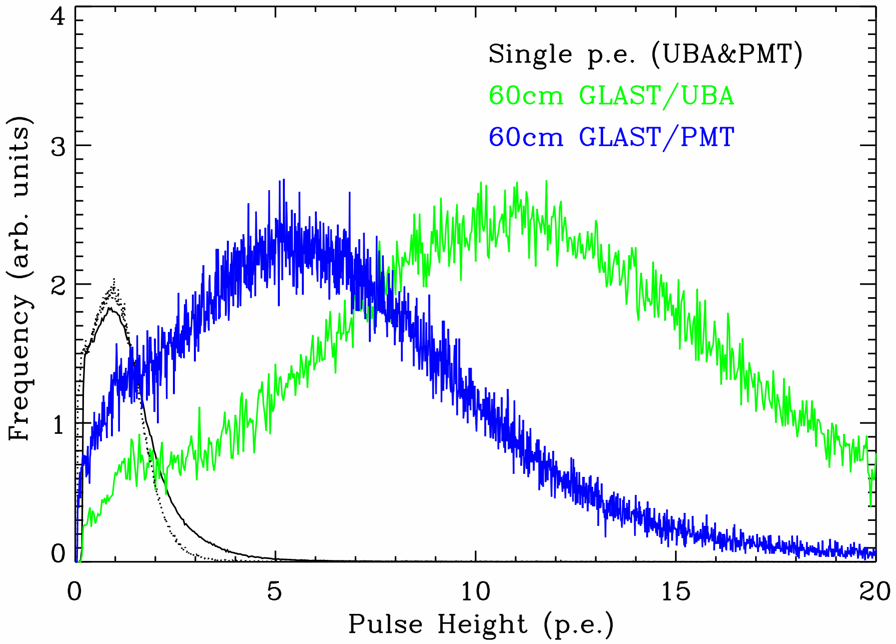




FiberGLAST measurements with conventional MAPMTs

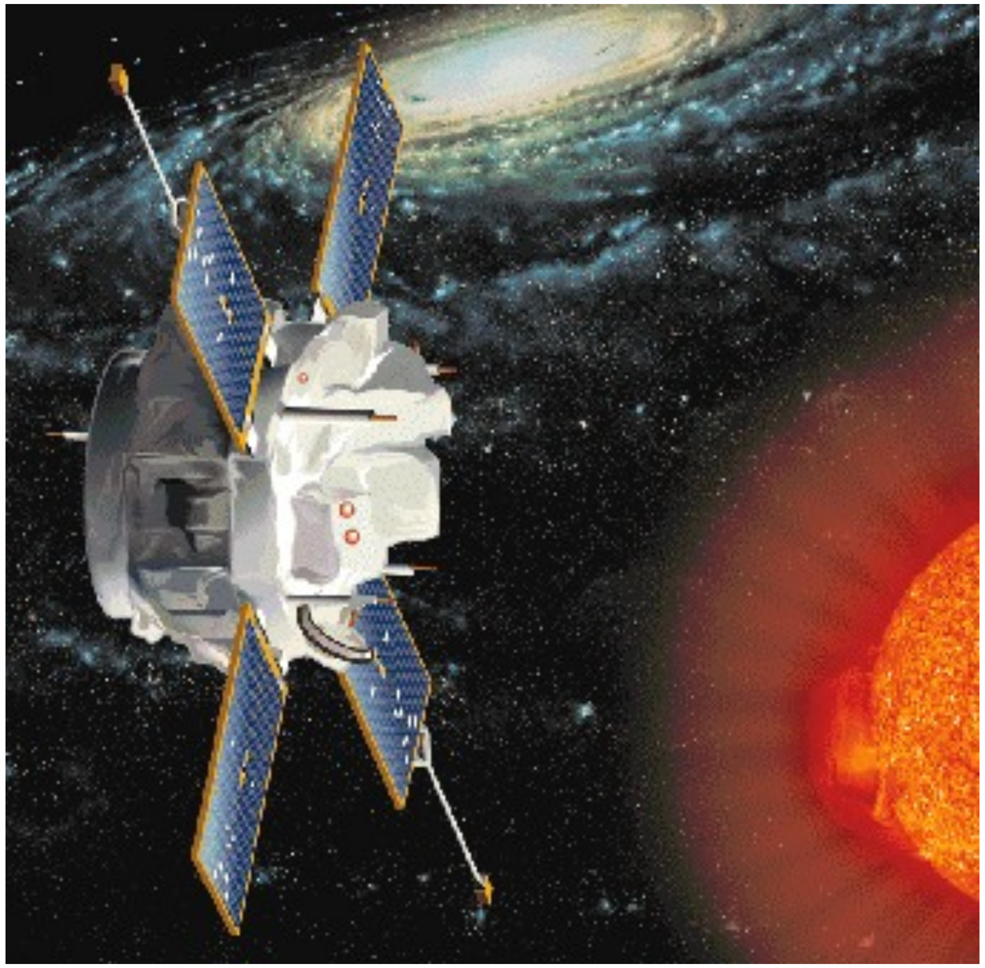


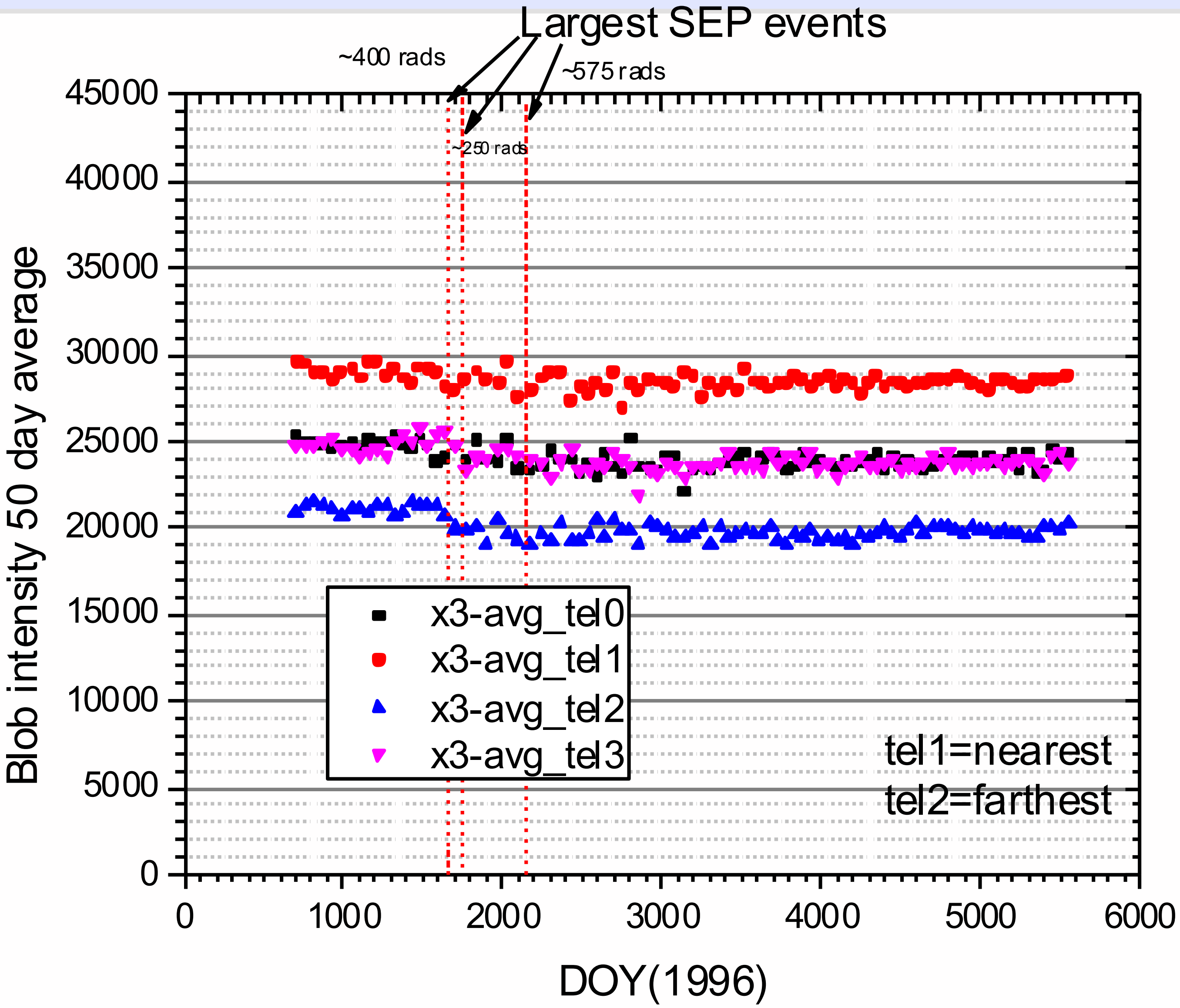
APT measurements with UBA PMTs lower efficiency fibers (10 p.e./MIP)



A simple extrapolation implies that APDs may allow us to reach 20 p.e./MIP at 1 m

TR Level? Fiber Aging?





- ACE has been in orbit about the L1 libration point, and operating for 17 years (since 1998). Only small drop in signal intensity (could be fibers or image intensifier aging)
- Radiation dose calculated by extrapolating study using NRL creme code is 0.4 kRad/year.
- HEP testing of older fibers show insignificant damage up to ~50 kRads based on data available in 1999 (FiberGLAST proposal). New radiation resistant fibers may be better - accelerator studies needed.

Past Work

3DTI FiberGLAST

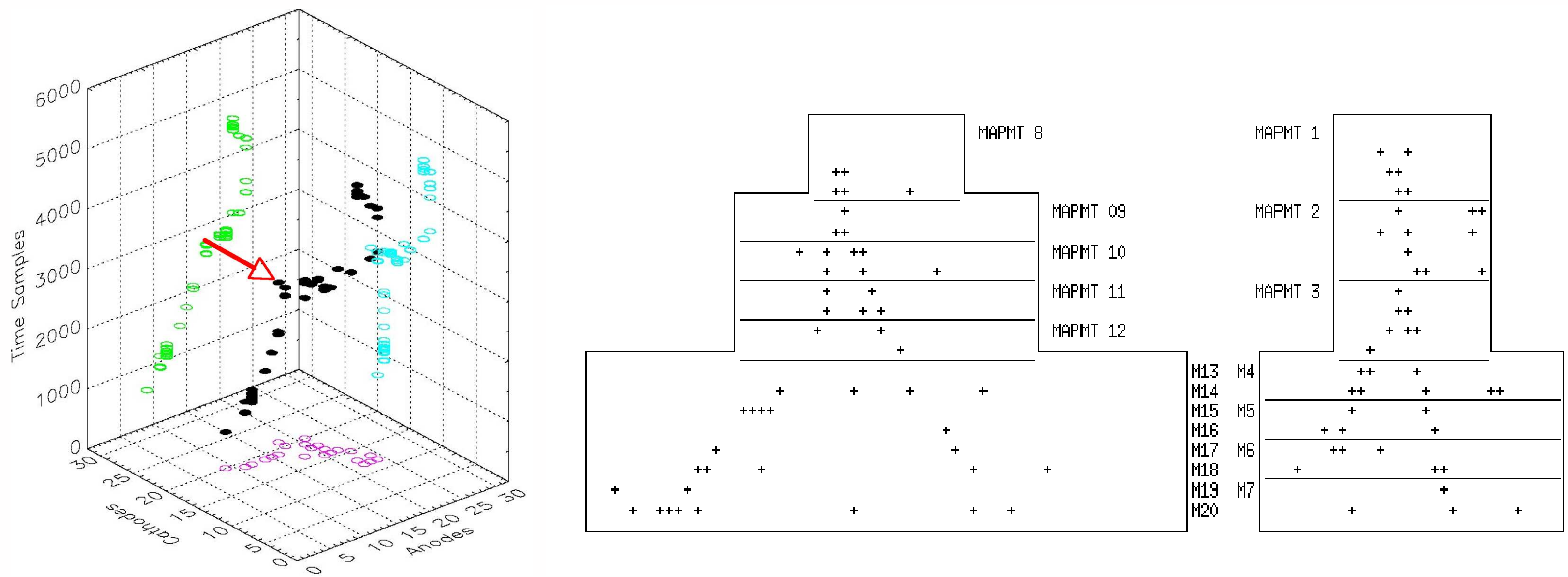


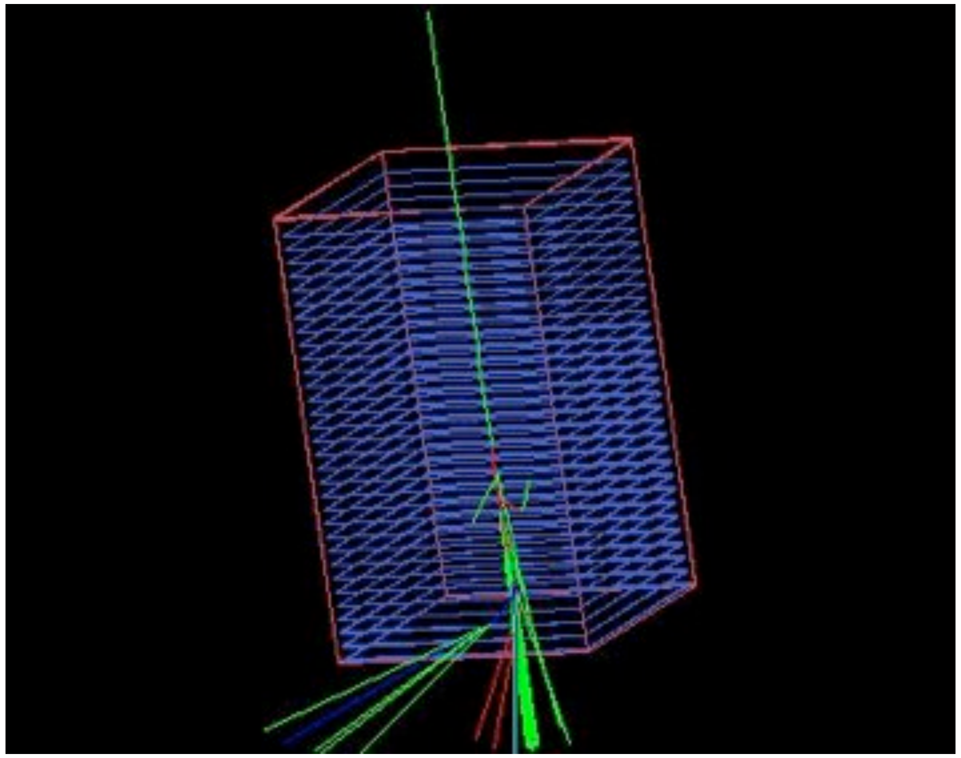
Figure 5: *Left:* Three-dimensional track image of a 6 MeV gamma-ray converting to an electron-positron pair, black dots. The $x-z$, $y-z$, and $x-y$ projections are also shown as green, blue, and purple open circles, respectively. Truncation of the tracks at the edges of the active detector volume prevents complete reconstruction of this event. The estimated incident photon direction is indicated by the red arrow. *Right:* Pair event in FiberGLAST prototype tracker measured during the CAMD accelerator run.

Weight and Power Budget

	Power	Mass	
TGT	208 W	1005 kg	40,000 channels 1.5 mW, EGRET design
TFTC	1212 W	4061 kg	320,000 channels 1.5 mW, 5000 MAPMTs
ACD	65 W	1065 kg	320 tiles, scaled from GLAST design
Central electronics	310 W	180 kg	Based on past missions, standard efficiency factors
Instrument structure		2153 kg	25% payload mass, spacecraft interface, ACD support
Total mission resources:			
Total Power	1796 W		
Total Active Mass	2504 kg		
Total Passive Mass	5960 kg		
Total Mass w/Spacecraft	10,963 kg		Spacecraft mass from CASTER estimate
Telemetry rate	500 kbps		Based on 10 times GLAST data rate

Launch Vehicle	Fairing Diameter	Approx Static Envelop	Payload to LEO (kg)
Falcon 9	4.6	4.37	13150
Atlas V 521	5.4	5.13	13490
Atlas V 401	4	3.8	9797
Delta IV M	5	4.75	12820
Dnepr-1	3	2.85	4500
Zenit 2	3.9	3.705	13740

APT Simulation Results



- 5 radiation lengths total
- 32 x-y 2.5m x 2.5m planes of 1mm fibers
- A_{eff} and PSF from reconstructed events, Energy resolution only from a PDG estimate!

$$\frac{E_{\text{leak}}}{E_0} = \frac{1}{\Gamma(a)}\left(1 - \int_0^{0.5t} z^{(a-1)} e^{-z} dz\right)$$

$$a = 2.0 + 0.5 \ln E_0$$

$$\frac{\Delta E}{E_0} \approx 0.59 \left(\frac{E_{\text{leak}}}{E_0}\right)^{0.73} \quad \frac{\Delta E}{E} < 50\% \Rightarrow t > 4$$

Table 2: Simulation results for TFTC and GLAST

		APT/TFTC		**GLAST**	
Energy (GeV)	Angle of Incidence θ (deg)	Angular Resolution σ_{68} (deg)	Effective Area A_{eff} (cm^2)	Angular Resolution σ_{68} (deg)	Effective Area A_{eff} (cm^2)
0.10	10	3.0	28,500	6.6	2,810
0.10	30	3.2	32,300	6.6	2,390
1.0	10	0.51	34,400	0.92	7,330
1.0	30	0.55	41,000	0.92	6,240
10.0	10	0.19	34,600	0.18	8,600
10.0	30	0.12	41,400	0.18	7,700
100.0	10	0.08	35,000	0.082	8,500
100.0	30	0.08	44,400	0.082	7,200

Note: This is far from the optimal geometry, track reconstruction

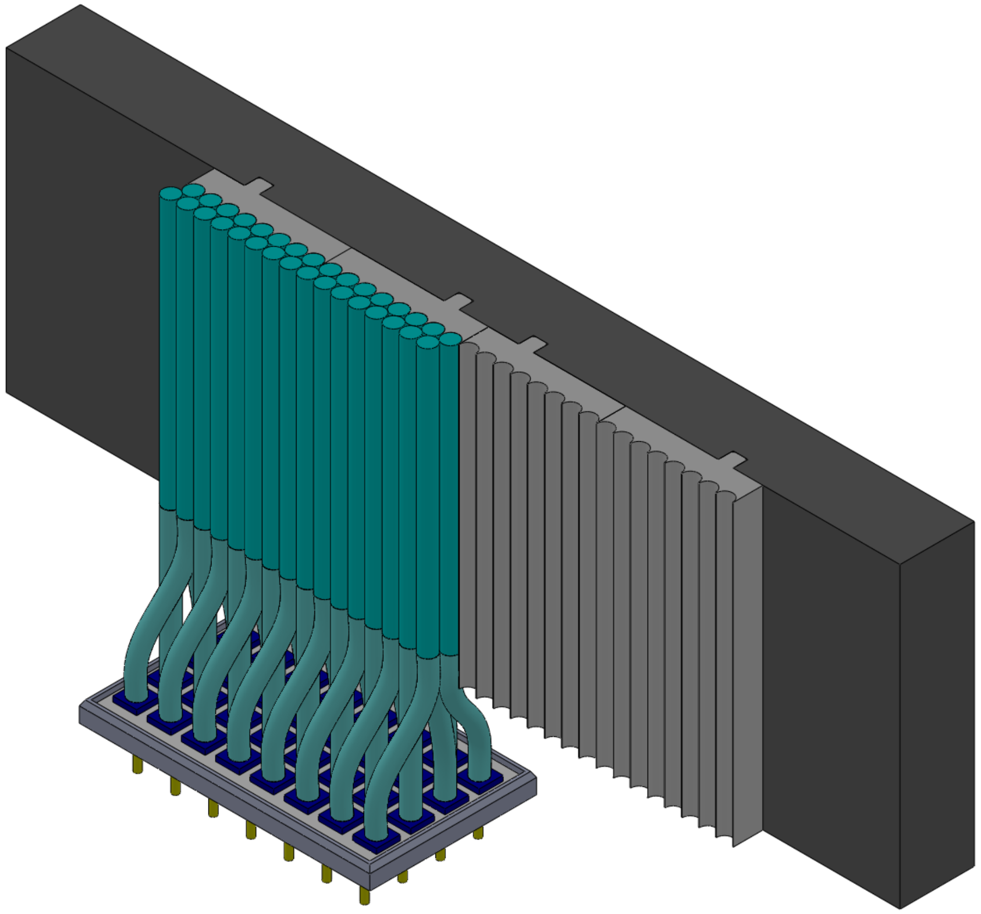
Cost Estimate

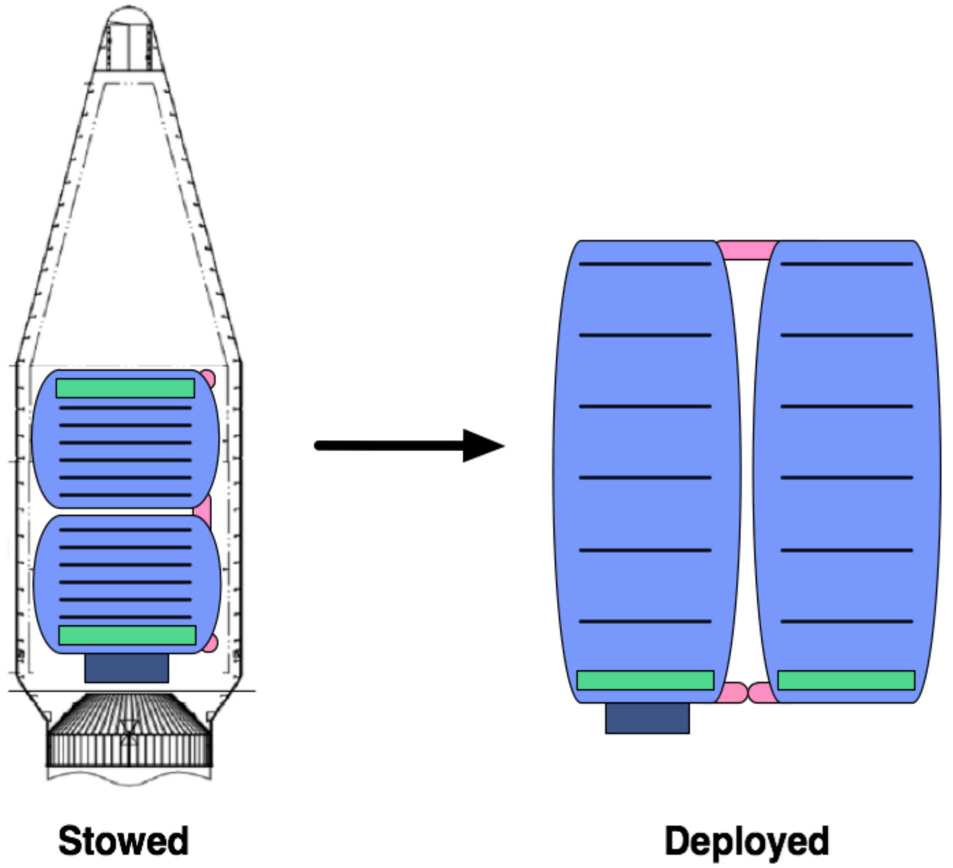
Astrophysics Strategic Mission Concept Study--Estimate of Mission Cost (FY-08$)

Cost Element	Ph-A (0.5yr)	Ph-B (1.5yr)	Ph-C/D (3 yr)	Dev. Tot	Ph-E (5 yr)	Mission Total	Cost Methodology
1.0 Project Management	0.2	1.0	9.0	10.2	1.2	**11.4**	9% of payload hardware cost B- D; 8% of Mission Ops
2.0 Mission Sys Engr	0.2	0.9	8.1	9.2	0.0	**9.2**	90% of Project Mgmt, Phase A-D Only
3.0 Mission Assurance	0.1	0.4	3.2	3.7	0.0	**3.7**	40% of System Eng, Phase A-D Only
4.0 Science	0.3	0.9	1.8	3.0	9.8	**12.8**	Derived by analogy with EGRET. 4 FTE Phase A-D. 15 FTE, Phase E
5.0 Payload	2.0	11.1	100.0	113.0	0.0	**113.0**	Experiment team estimate based on analagous/heritage instruments and experience
5.1 Gas Microwell Tracker	0.6	6.4	22.0	29.0	0.0	***29.0***	Based on known costs from development program at GSFC, ASIC and electronics costs for GLAST and SWIFT, and gas system from EGRET.
5.2 Fiber Tracker	0.9	10.1	35.0	46.0	0.0	***46.0***	Based on recent quotes for fibers and MAPMTs and by scaling from HNX and FiberGLAST costs
5.3 ACD	0.8	8.4	28.9	38.0	0.0	***38.0***	Based on scaling from ACD built for GLAST
6.0 Flight Systems	3.0	22.0	125.0	150.0	0.0	**150.0**	Based on RDSO ROM Costing + Input from GSFC Costing Estimator.
7.0 Mission Ops	0.0	0.0	2.0	2.0	15.0	**17.0**	Scaled from GLAST estimated costs
9.0 Ground System	0.0	0.0	7.0	7.0	4.0	**11.0**	By analogy to GLAST
10.0 System I&T	0.5	3.3	22.5	26.3	0.0	**26.3**	10% of hardware cost
Sub total	**6.2**	**39.5**	**278.6**	**324.3**	**30.0**	**354.3**	
Reserves		11.9	83.6	95.4	4.5	**99.9**	30% on Phase B-D; 15% on Phase E
Sub total w/reserves	**6.2**	**51.4**	**362.2**	**419.8**	**34.4**	**454.2**	
Elements w/o cont:							
8.0 Launch Vehicle	0.0	0.0	234.0	234.0	0.0	**234.0**	Estimate of Atlas-V 521 from ELV info for study
11.0 E/PO	0.0	0.1	0.7	0.8	0.1	**0.9**	.25% of Phase B-D cost before reserve
12.0 Technology Dev.						**10.0**	TGT (3-DTI) Technology Development
Mission Total:	**6.2**	**51.5**	**596.9**	**654.6**	**34.5**	**699.1**	

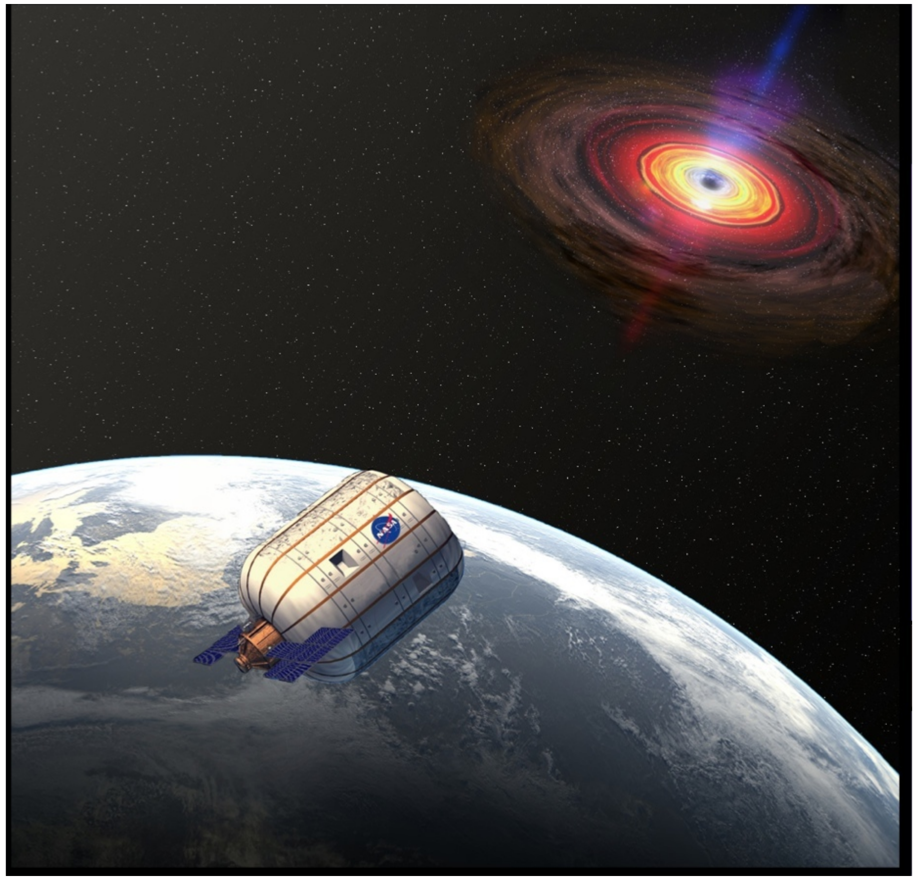
Technology Development

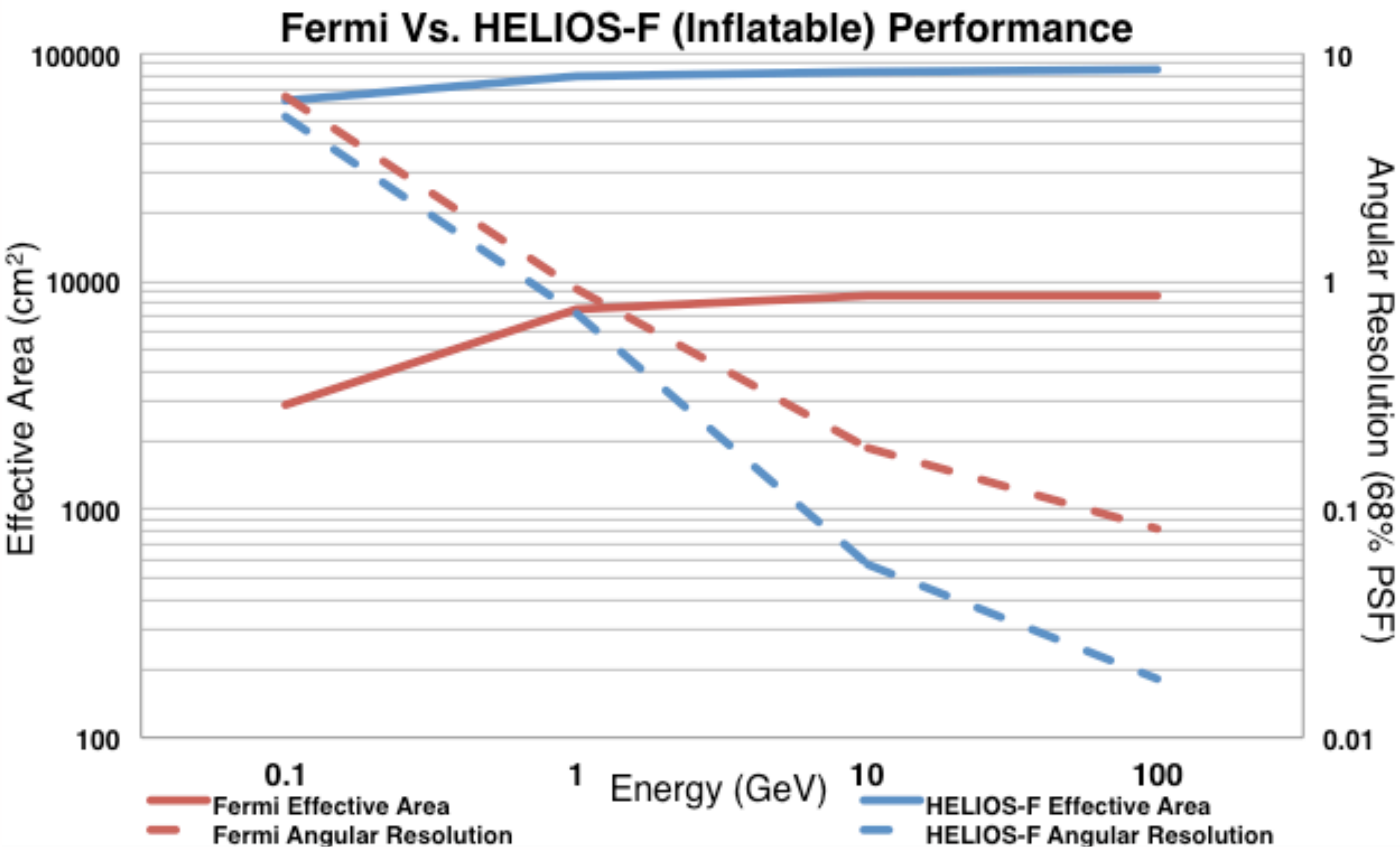
- Demonstrate and Qualify New Photodetector/Readout Electronics:
  - ✳ **SiPMs** (with better crosstalk) or APDs (with <30 e- readout) for readout offer QEs>70% QE - (*sufficient that MIPs in 1mm fiber will produce ~20 p.e., can set threshold above single p.e. threshold for noisy Si devices*)
  - ✳ **ASIC development**: Existing ASICs already close to this performance, e.g., 32 or 128 channel Brookhaven ASIC used for X-Caliber - PolStar CZT ASICs might share common design.
- Simulation Studies Optimize Fiber Geometry:
  - ✳ Low cost readout allows more channels with interleaved fibers, improved angular resolution and efficiency (but more channels).
- **Qualification of fibers**: Radiation tolerance studies, thermal-vac testing
- Explore **deployables**, new platforms but need to developing believable cost model!





Large Deployed/Inflated Fermi



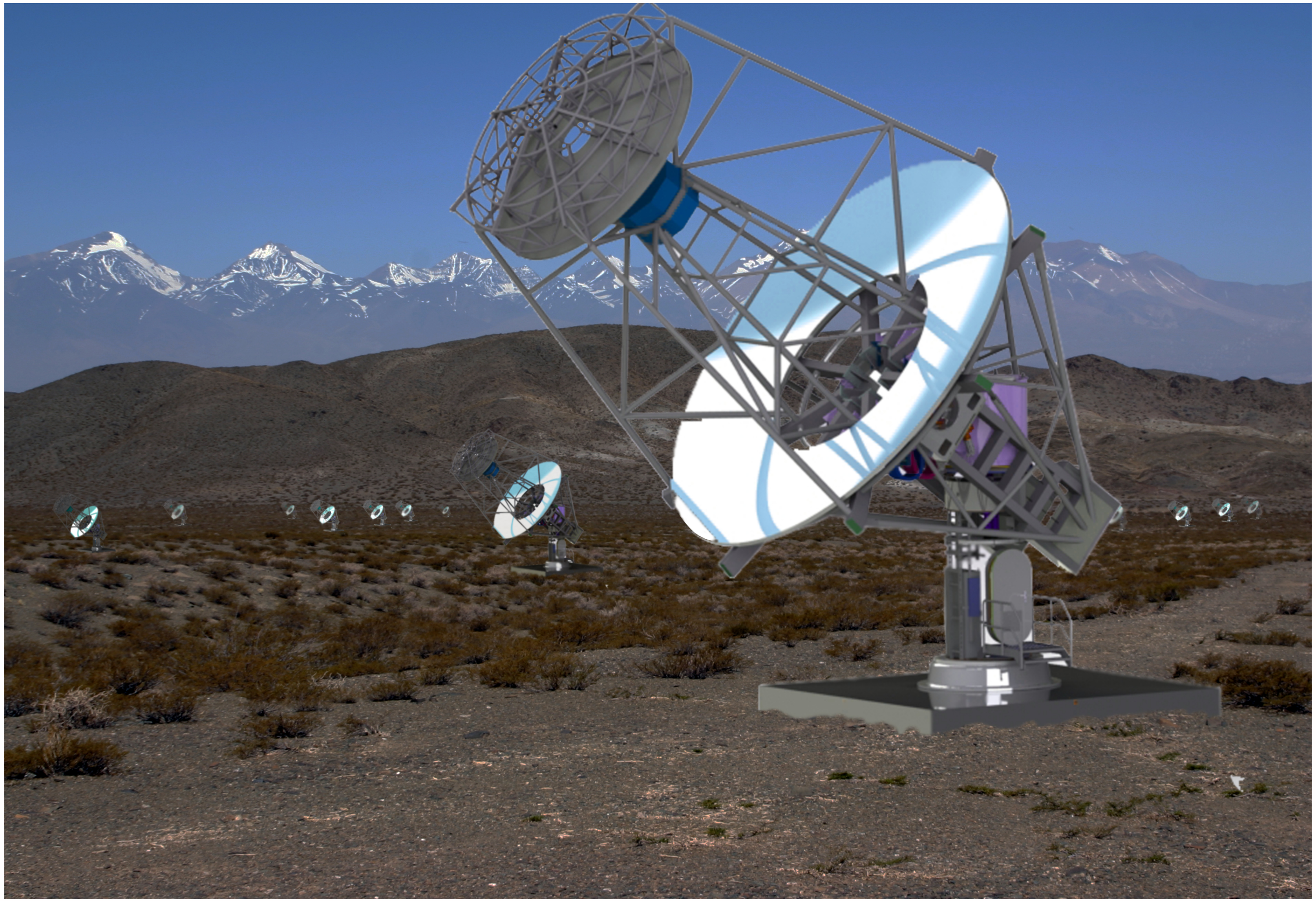


	HELIOS-F	Fermi	units
Mass	6350	4303	kg
Power	2800	3120	W
Instrument Height	6.3	0.72	m
Instrument Area	8.64	3.24	m^2
Mission Duration	5	5	y
Orbit	600 km, equitorial	565 km, 23.5˚	
Cost	333-590	762	$M FY15

- Engineering cost study by JPL engineer, R. Amini - design optimized for area and angular resolution (not geometry factor)
- Scaling law by simple quadratic addition of angular resolution (detector pitch) and multiple coulomb scattering (normalized to APT/Fermi)
- Angular resolution improves from separation of planes possible with a deployable detector.

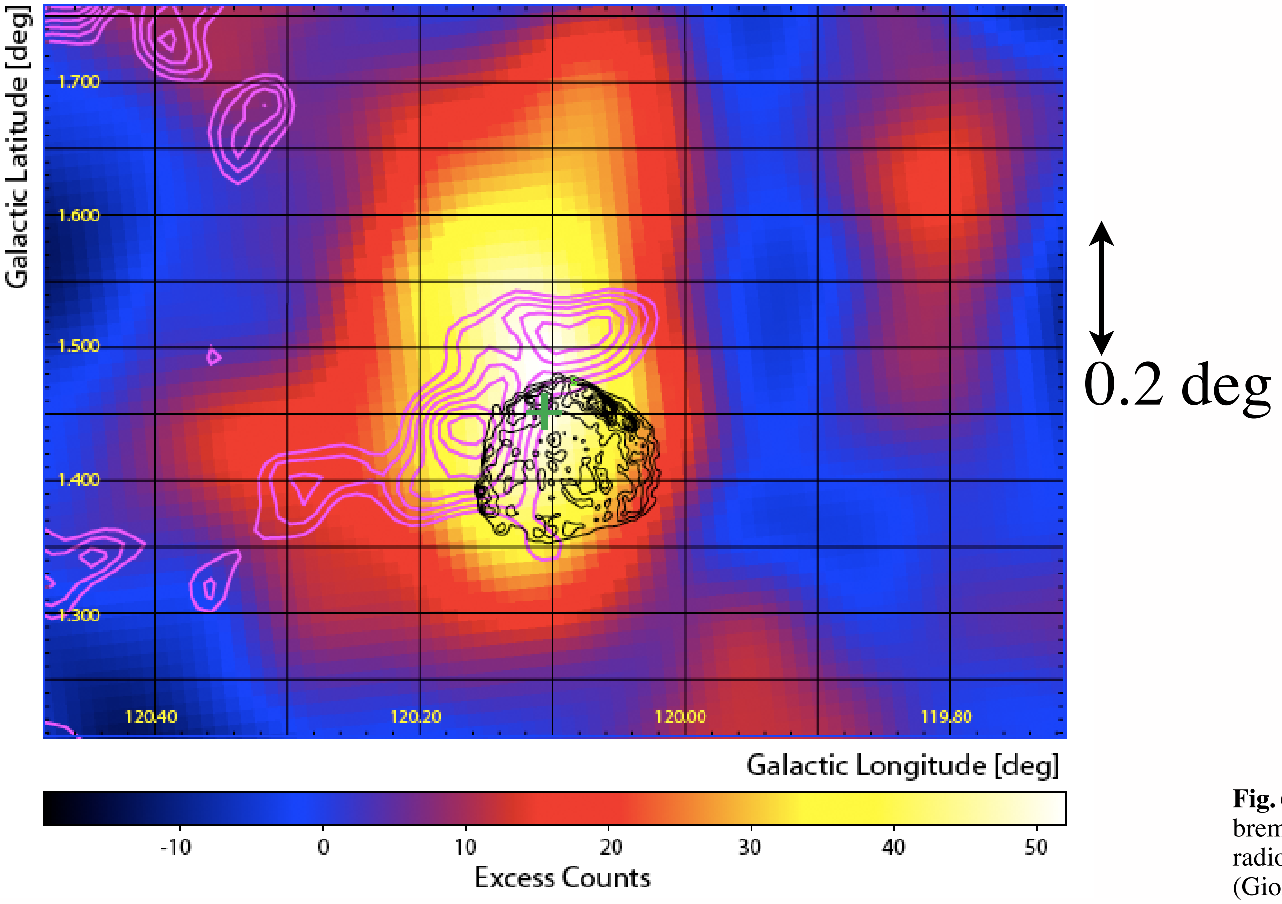
Tail Calorimeter?

- There are numerous purpose-built (narrow-field) optical telescopes, how about another narrow-field telescope for >100 GeV gamma-rays?
- Might be able to use relatively small (6m) telescopes at, e.g., HAWC site to achieve this threshold.
- To support APT, a dedicated fast-slewing, narrow field (6deg) array at an existing site might provide good "tail calorimetry" (with >4 o.m. in area!) at hundreds of GeV. HAWC will take over at higher energies (>TeV). Estimated cost ~ $30M



Tycho - A Case Study

VERITAS Tycho Image



VERITAS Tycho Image

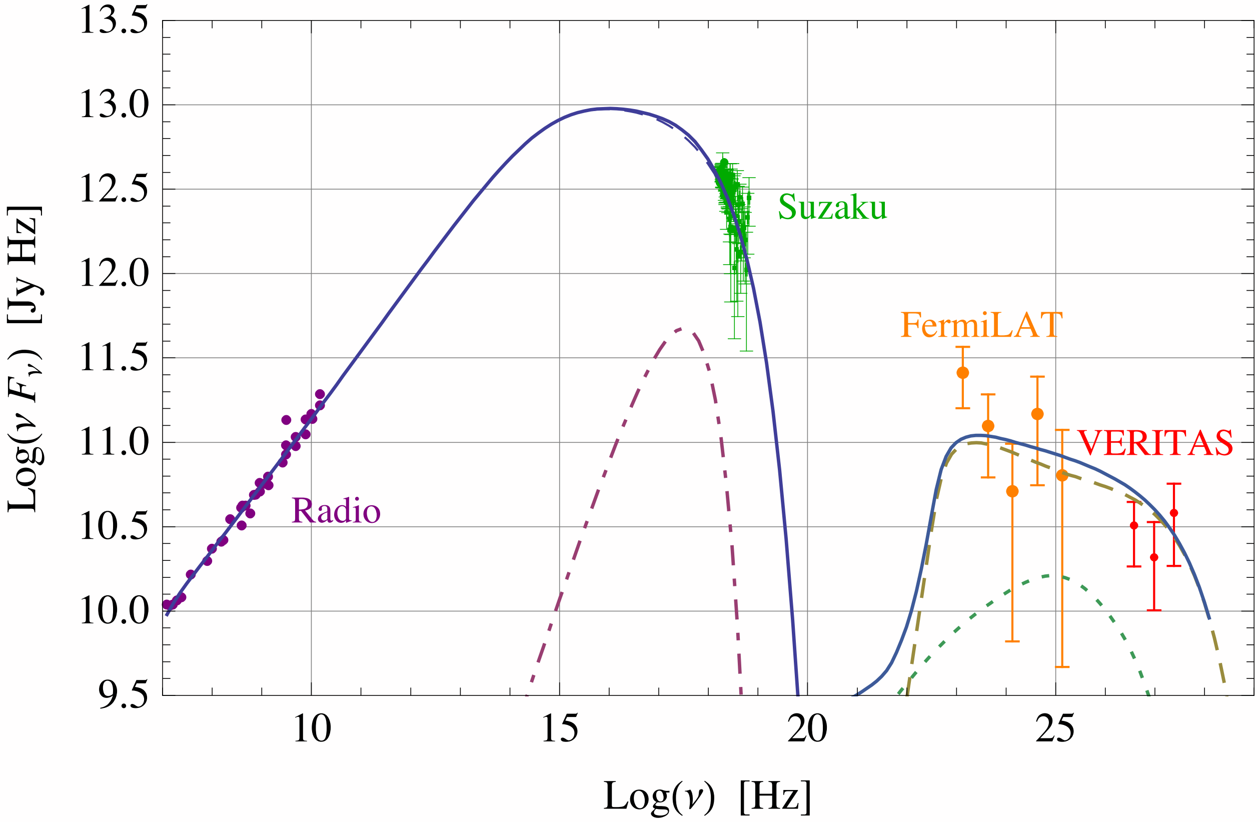


Fig. 6. Spatially integrated spectral energy distribution of Tycho. The curves show synchrotron emission, thermal electron bremsstrahlung and pion decay as calculated within our model (see text for details). The experimental data are, respectivley: radio from Reynolds & Ellison (1992); X-rays from *Suzaku* (courtesy of Toru Tamagawa) , GeV gamma-rays from Fermi-LAT (Giordano et al., 2011) and TeV gamma-rays from VERITAS (Acciari et al., 2011). Both Fermi-LAT and VERITAS data include only statistical error at 1 σ.

(Morlino and Caprioli, A&A, 2011)

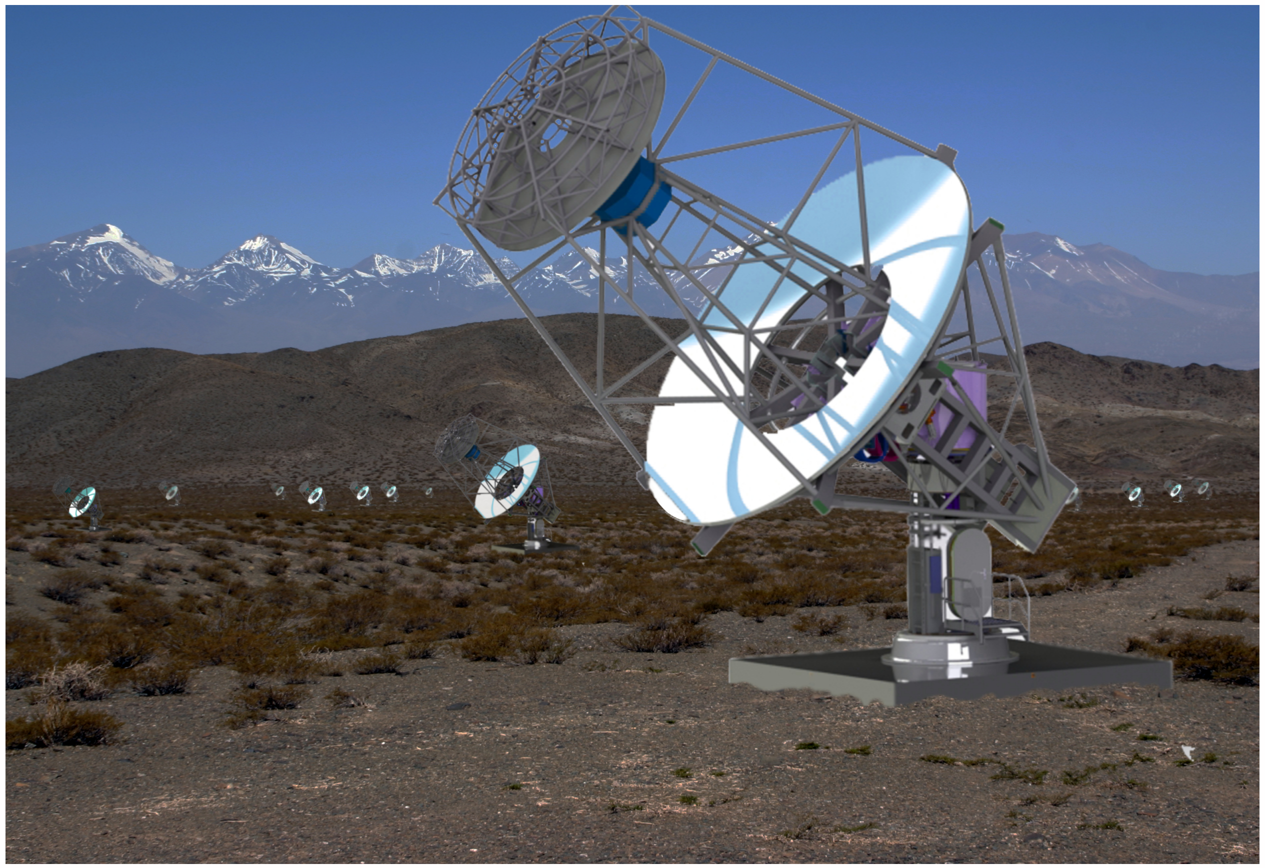
- Even VERITAS 0.1 deg PSF not sufficient
- Would a pion cutoff tell us about the Tycho SNR, versus diffuse cosmic-ray pions from the molecular cloud?
- Would better energy resolution with Fermi Help?
- Didn't we really learn about the origin of hadronic cosmic rays from joint Fermi VERITAS spectrum?

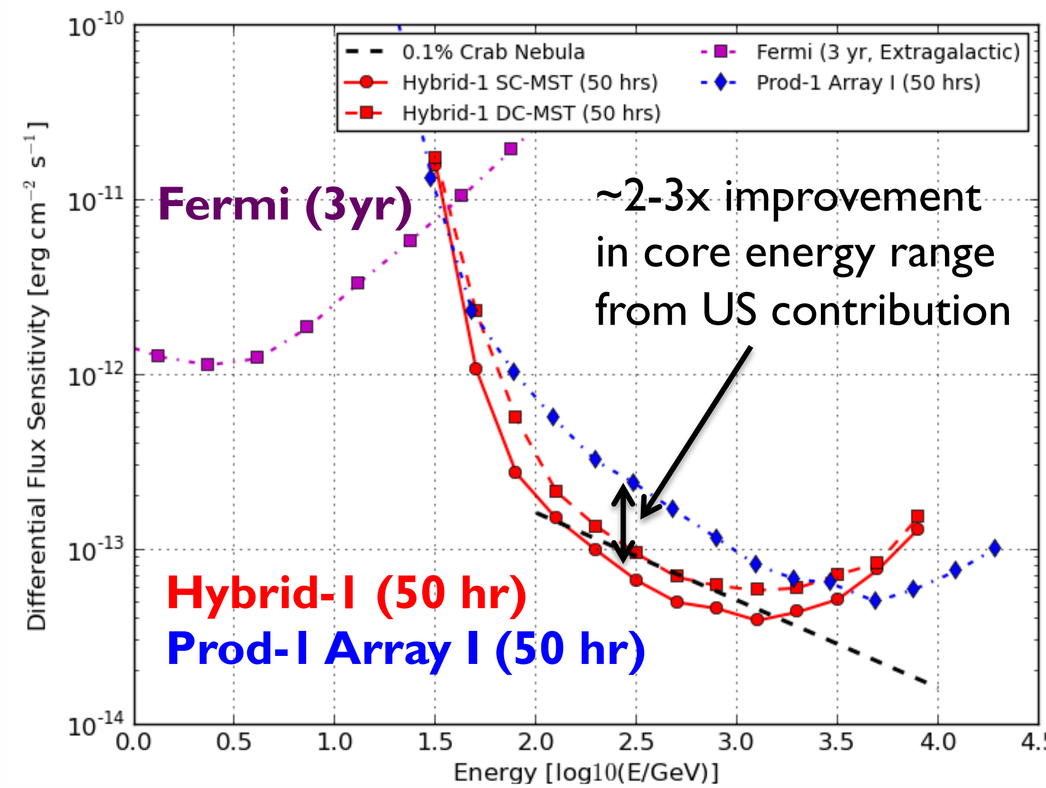
Conclusions

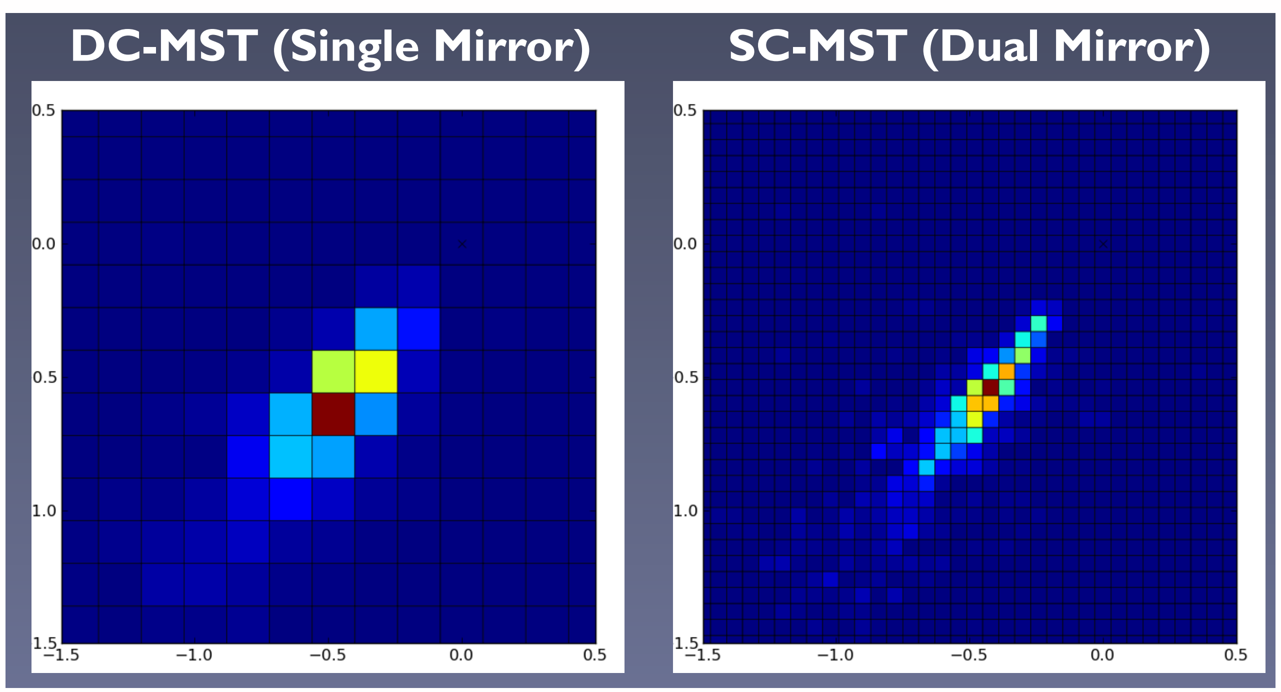
- Big Science objectives: Cosmology (DM, Primordial fields, Hubble constant, baryogenesis, first Pop III stars - explosions and imprint on EBL)
- It might be possible to achieve an order of magnitude geometry factor, large improvement in angular resolution by giving up energy resolution and embracing new (less robust) technologies.
- Don’t forget the power of GeV measurements! Just because the MeV regime is more challenging and there is a gap, it doesn’t mean it is the only game in town.
- When designing space experiments don’t forget about the strengths and weaknesses of ground-based instruments!

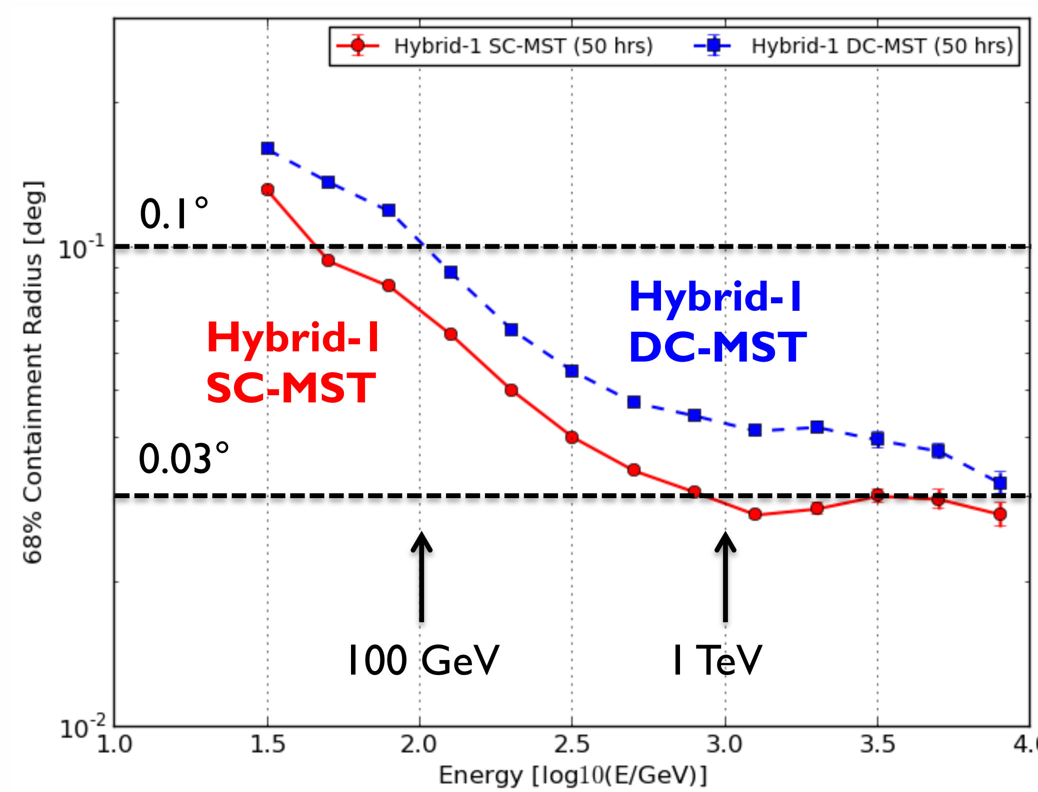
Backup Slides

Tail Calorimeter?







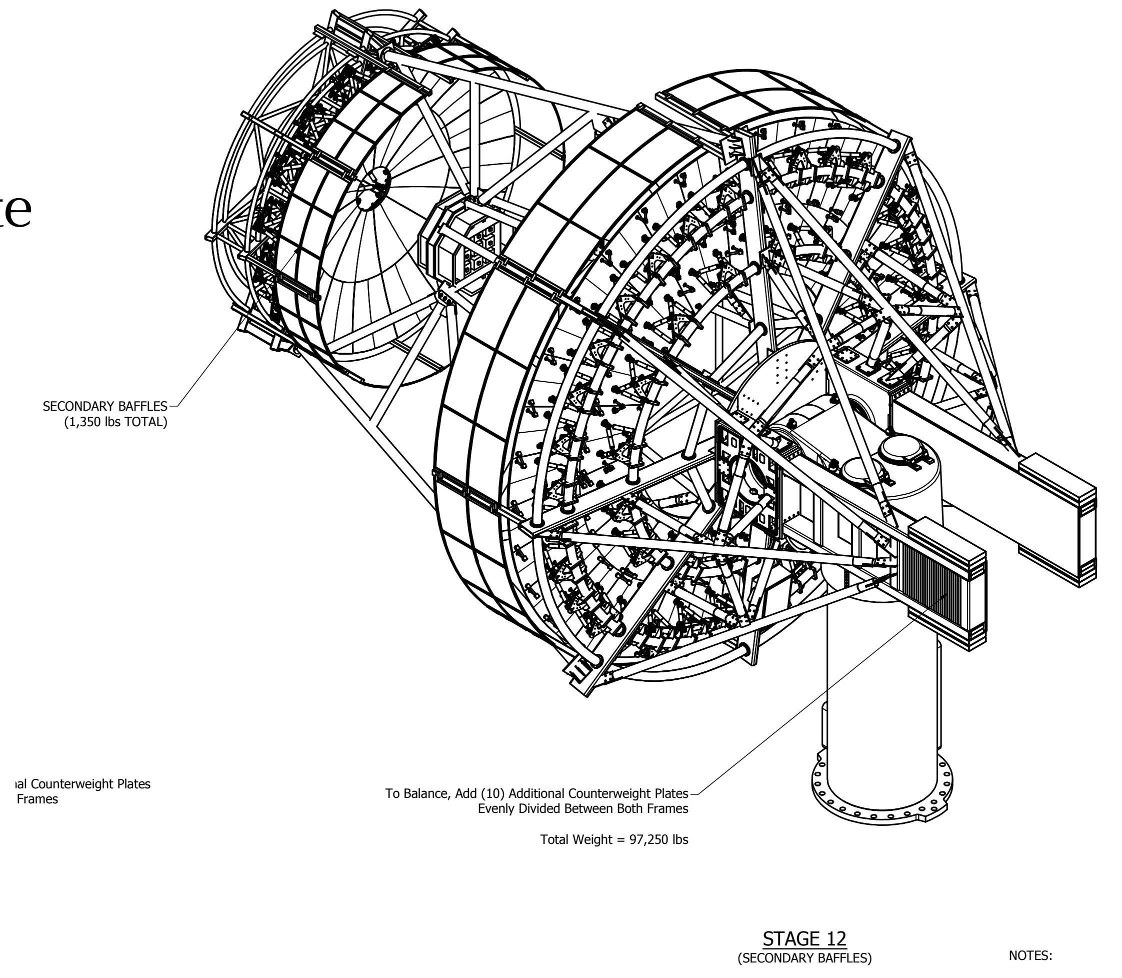


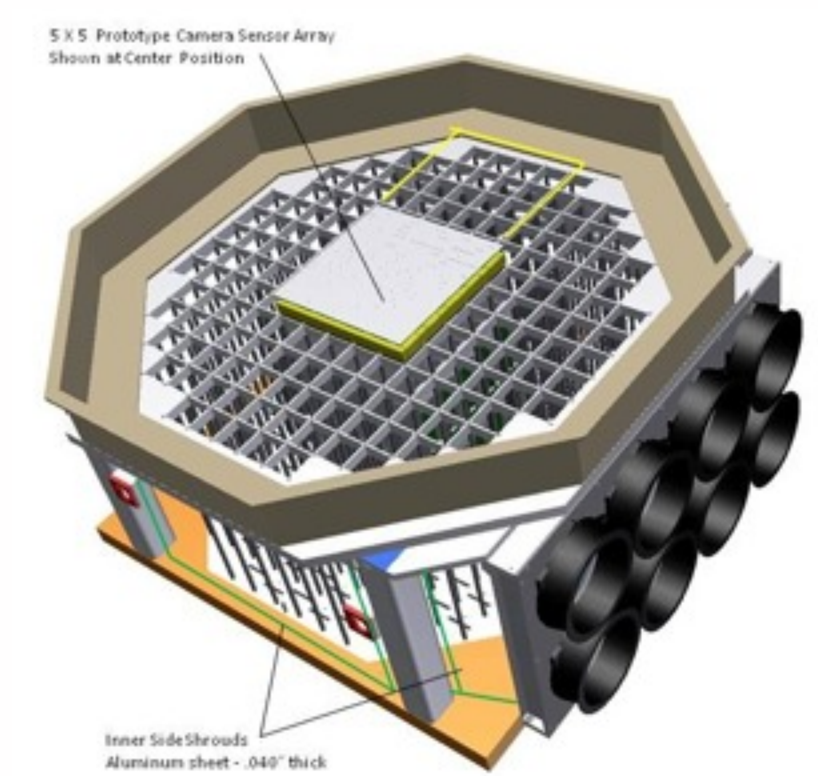
pSCT Telescope

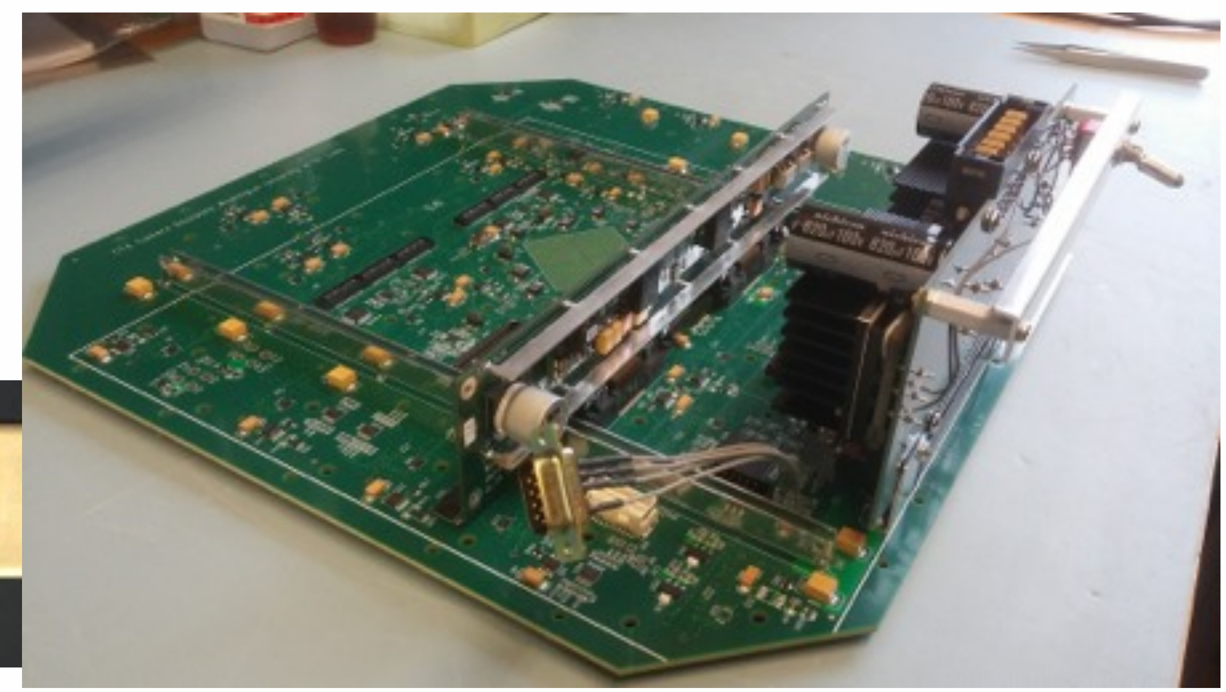
- SiPM camera providing lots of experience with Geiger-mode APDs relevant to APT.

- Telescope design complete (left), assembly plan complete (right), OSS has gone out for bid, procurement will start soon.

- Most components of the camera are under construction, first complete modules/PCBs currently under test







Energy Resolution?

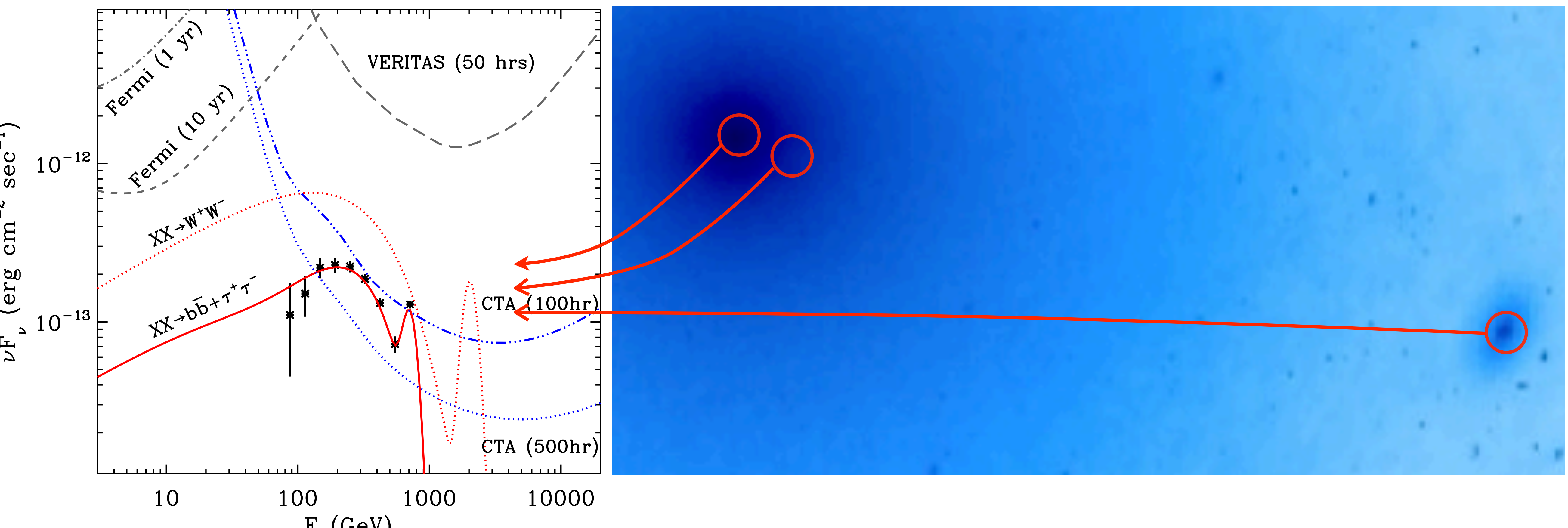
- Trade calorimetry for effective area and FoV (LAT 2.5 m^2 str)
  - ✳ Total instrument thickness (R.L) and number of layers still needs to be studied.
  - ✳ AGILE had thin design, about 3 radiation lengths. Studies showed that multiple coulomb scattering could be used for energy reconstruction up to GeV energies. Highest energy spectral points (at 100% resolution) around 8 GeV - *Aldo Marselli*
  - ✳ Si was best choice for GLAST (stability, etc.) but need to reduce cost with a new technology - fibers.
  - ✳ Lower cost, hrobust readout (APDs+ASICs) needed to allow longer fibers

Tough Question CF12

``Given large and unknown astrophysics uncertainties (for example, when observing the galactic center), what is the strategy to make progress in a project such as CTA which is in new territory as far as backgrounds go? How can we believe the limit projections until we have a better indication for backgrounds and how far does Fermi data go in terms of suggesting them? What would it take to convince ourselves we have a discovery of dark matter?''

Backgrounds get lower at higher energies, but even at 1-3 GeV with no background subtraction get a limit within $1^\circ \sim 1 \times 10^{-7}\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \Rightarrow \langle \sigma v \rangle = 1.6 \times 10^{-25}\ \mathrm{cm}^{3}\mathrm{s}^{-1}$

(Tim Linden, SLAC CF meeting)



Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by ~$E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.

General Thoughts

- Should push for probe-class missions (>Explorer, <1 G$)
- A large (>G$) mission is very unlikely
- We should produce a mission concept that clearly identifies a few science drivers, and a strawman for the technological approach.
- Accurate costing may include development of more accurate parametric models for large dumb volumes, deployables etc.